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Urban carbon flow and structure analysis in a multi-scales economy

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ABSTRACT

With the increasing threat of global climate change, carbon emissions reductions in cities have aroused the concern of the world. Carbon flow is one of the profiles that is closely connected to the urban metabolic system. Here, a global environmentally extended multi-scale input-output model was employed to accurately trace the carbon flow in a multi-scales economic system from production and consumption perspectives. Beijing was selected as the case, and the results were as follows: Beijing is typically a net importer of carbon flow (net consumer), which is consistent with Beijing's profile as a consumer metropolis. Further, all seven domestic regions in China were net producers corresponding to Beijing, supporting nearly 96.56% of the net carbon inflows driven by Beijing's final demand. Beijing mainly imports carbon flows from domestic regions and developing areas around the world, while exporting little to developed countries. Aside from the Mining (S2), Nonmetallic (S9), and Transport (S17) sectors, all other industrial sectors were net inflows of carbon for Beijing in 2010. In addition, Beijing is located at the bottom of the global production supply chain, transferring the embodied carbon flow to the origin by domestic and international imports. These results indicate that regional coordination and regional trade structure adjustment should be the main measures to tackle global climate change in the future.

1. Introduction

Currently, 54% of the world's population lives in urban areas, a proportion that is projected to increase to 66% by 2050 with the expected addition of 2.5 billion people to cities (UN, 2014). Cities around the world will face numerous problems in meeting the increasing needs of their urban populations. In fact, they already consume 67–76% of global energy (Seto et al., 2014) and produce 75% of the carbon emissions (IPCC, 2006). Cities are among the main causes of global environmental issues but could also be the place for solutions to many environmental stressors. With the increasing threat of global climate change, carbon emissions reductions in cities have aroused the concern of the world (Seneviratne et al., 2016). Urban carbon accounting induced by energy consumption has been widely conducted in recent years (Chen et al., 2017; Shao et al., 2016; Lin et al., 2013; Liu et al., 2012; Meng et al., 2017a, 2017b). Carbon flow is one of the profiles that is closely connected to the urban metabolic system (Chen and Chen, 2016; Zhang et al., 2014). It is also a valuable indicator in understanding both direct and indirect on-site and off-site greenhouse gas (GHG) emissions (Zhao et al., 2014; Lin et al., 2015; Wright et al., 2011).

Regarding CO_2 emissions at the city level, an open urban economy induces CO_2 emissions beyond its geographic boundaries via both international and domestic trade (Lin et al., 2017; Hu et al., 2016). Many studies demonstrate that a large number of virtual emission fluxes (including many air pollutants) flowing into, within, and out of the city associated with economic flows (Chen et al., 2013, 2017a; Meng et al., 2015, 2016; Shao et al., 2016; Feng et al., 2014). Considering the full impact of urban activities on global carbon emissions, accurate carbon flow analysis at the city-scale faces many challenges. Therefore, the responsibility for urban CO_2 emissions reduction should not be confined to the local government but should include collaboration among local, regional, national, and global policymakers by considering industry specializations and trade policy differences (Feng et al., 2013, 2014). The issues that need to be addressed include how to accurately trace urban carbon flows embodied in domestic and foreign trade and how to allocate responsibilities for an urban economy's carbon emissions.

Research has mainly concentrated on urban carbon flows through production-based accounting (PBA) and consumption-based accounting (CBA) approaches. Production-based or territorial-based carbon flows

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are caused by domestic production, including exports (Peters and Hertwich, 2008b). They neglect indirect carbon emissions embodied in the supply chain, resulting in carbon leakage, which undermines the effects of international climate policies (Atkinson et al., 2011; Steininger et al., 2014). Currently, the PBA approach is widely used in global climate change agreements, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (Mi et al., 2016). The CBA approach allocates emissions occurring along both production and distribution to the final consumers, rather than the producers (Brizga et al., 2017). Consumption-based carbon flows include imports emissions embodied in trade, but they exclude exports. The CBA has been increasingly used in a policy context to provide an understanding of the emissions embodied in trade (Mi et al., 2016). A series of studies compare the two approaches and demonstrated the advantages of CBA (Jakob et al., 2015; Lin et al., 2015; Peters and Hertwich, 2008b). In particular, CBA opens the door to new solutions to assign carbon emissions, bringing together producers and final consumers. Moreover, it can improve both cost-effectiveness and justice, providing a more useful and straightforward evaluation of the performance of local climate actions and of the green level of upstream and downstream production technologies, resolving carbon leakage, promoting environmental comparative advantages, increasing options for CO_2 emissions mitigation, and encouraging technology diffusion (Peters and Hertwich, 2008a; Larsen and Hertwich, 2009; Chen et al., 2013; Steininger et al., 2014).

Input-Output Analysis (IOA) is the main CBA approach used to trace urban carbon flows. When city-level input-output tables are not available, life cycle analysis (LCA) is also a complementary tool for evaluating the carbon flows of an urban economy (Chen et al., 2017; Meng et al., 2017a). In previous studies, the single-regional input-output method was used to estimate urban carbon emissions embodied in imports. However, due to limited data availability, it is generally based on the homogeneity assumption that imported and domestic products from the same industries are all produced with the same technologies and that their embodied intensities are equal (Meng et al., 2017a; Mi et al., 2016). This induces inaccurate results, especially for a modern open city supported by massive domestic and foreign imports. Indeed, embodied intensities at different economy scales can vary widely due to diverse economic structures and productive technologies (Chen et al., 2013). Hasegawa et al. (2015) find that the percentage of carbon leakage to carbon emissions is more than 50% on average at the regional level, based on a multi-regional input-output (MRIO) model. Thus, it is important to differentiate the carbon flows embodied in trade and consumption at different scales.

The multi-scale input-output (MSIO) model revised from the MRIO can provide more comprehensive analysis capable of capturing the interdependencies of the global economy while preserving regional differences (Chen et al., 2011; Bachmann et al., 2014). It has been developed and often used at large scales to concentrate on contemporary issues such as greenhouse gas emissions (Wiedmann, 2009; Feng et al., 2014; Liu et al., 2016) and water footprints (Daniels et al., 2011). However, only a few studies have paid attention to urban carbon emissions accounting by extending the research scale to the global supply chains (Chen et al., 2013; Shao et al., 2017; Lin et al., 2017), mainly because city-level input-output tables are not available (Chen et al., 2017). For those existing studies, the MSIO model was used to only trace the consumption-based carbon flow and account for territorial CO_2 emissions at the point of production without consideration of where goods are used or who ultimately uses them (Atkinson et al., 2011; Steininger et al., 2014). This ignores the fact that a large amount of goods and services produced by urban economies, especially those Asian cities (Oliveira et al., 2013), may be exported to satisfy the demand of other regions worldwide; On the other hand, the MSIO model captures the relationships between the city and trading countries around the world, but it lacks domestic regional detail for China (Lin et al., 2017; Hu et al., 2016; Shao et al., 2016). Therefore, a multi-scale arithmetic for urban carbon flows is presented in this study to accurately trace the destination and source of various flows in the local, domestic regions and the worldwide economies, according to the general formulation of MRIO analysis for urban carbon emissions.

Beijing (longitude 116°25′29″ E, latitude 39°54′20″ N), the capital of the People's Republic of China, is the center of the nation's political, cultural, and education life and one of the four municipalities directly under the Central Government. It covers an area of 16,411 km^2, with a total permanent resident population of 19.60 million in 2010. During the period of 2000–2011, Beijing's economy developed rapidly, with the GDP reaching 1625.19 billion Yuan in 2011 and an average annual growth rate of 16.04% (BMBS, 2011). Especially after the Olympics Games held in Beijing in 2008, the Beijing industrial structure has been adjusted with many energy-intensive industries transferred to neighboring provinces. Beijing is in a post-industrial economy with three-quarters for the tertiary sector in 2010 compared to most other Chinese cities dominated by industrial sectors. As economies opened up after 2008, Beijing has closer relationships with many economies around the world, including mainland China regions (domestic trade) and foreign countries (international trade). This study aimed to employ an environmental-extended MSIO (EE-MSIO) modeling to accurately trace the spatial distribution of urban production-based and consumption-based carbon flow in the local, domestic, and worldwide range of the Beijing economy in 2010. The paper is organized as follows: 1) introduction to the calculating methodology and data source, 2) application of the EE-MSIO model to trace carbon flow for Beijing in 2010, and 3) drawing conclusions and policy implications based on results.

2. Methodology and data use

2.1. EE-MSIO model

The core of the EE-MSIO model, which was developed at three different scales (city, nation, and global), is a multi-regional input-output table (MRIOT) describing product exchanges within and among city-nation-globe economic systems. The objective was to merge two already existing and possibly conflicting MRIO datasets that describe different spatial scales into one multi-scale model. In particular, it links the MRIOT of Chinese provinces in 2010 with the World Input-Output Table (WIOT) in 2010, which is based on the World Input Output Database (WIOD).[1] It has the advantage that IO tables and trade flows do not need to be estimated at either scale (only trade flows linking scales) (Bachmann et al., 2015). Similar linkages have been used in previous studies (Feng et al., 2014; Mi et al., 2017; Su and Ang, 2014; Weitzel and Ma, 2014; Liu et al., 2016), and the main linking method was previously introduced in more detail by Peters et al. (2011).

In the EE-MSIO model, the world is divided into 41 nations or regions and 1435 sectors (35 sectors per nation/region) in the WIOD for each year (Dietzenbacher et al., 2013; Timmer et al., 2015). As China is one of the 41 regions in the WIOD, the Chinese IOT in the WIOD is disaggregated into 30 province-level tables, based on the IOTs within the Chinese MRIO model. This model consists of 30 provinces (including four cities), except Tibet and Taiwan. The main database of the Chinese MRIO, compiled by Liu and his colleagues (Liu et al., 2014), has been widely applied in related research (Feng et al., 2013, 2014; Liu et al., 2016). And the MRIOT of China for 2010 was the newest available data currently. The WIOD's international import and export matrices for China were also disaggregated and allocated to the 30 provinces, based on provincial exports and imports in the Chinese MRIOT. International exports for each sector in each province were distributed among importing sectors in foreign countries at the same ratio as China's total exports. The detailed equation follows:

[1] http://www.wiod.org.

$$T_{ij}^{ps} = \frac{T_{ij}^{Cs}}{\sum_s \sum_j T_{ij}^{Cs}} \sum_s \sum_j T_{ij}^{ps} \tag{1}$$

where, T_{ij}^{ps} is the export monetary flow from the i-th sector in region p to the j-th sector in region s in the WIODT. T_{ij}^{Cs} is the total export monetary flow from China to region s in the WIODT. The same formula can also be used to evaluate T_{ij}^{sp}. After the calculation of the EE-MSIO model, a coordinate matrix was used to combine the sectors from the two different MRIOTs into 20 sectors (Oita et al., 2016; Hu et al., 2016). Finally, the global economic system was divided into 70 regions and 1400 sectors (20 sectors per region) in the EE-MSIO model. The detailed sector classification is listed in Table S1. For simplicity in the results and discussion, the 70 regions are organized into eight Chinese regions and 10 world regions, listed in Table S2.

With the interconnection of different sectors in a city and those in different regions, the production-based and consumption-based urban carbon flows within the global economy can be assessed by the trade relationship in the EE-MSIO model. PBA investigates a city's role as a direct emitter, and urban production-based carbon flow represents its direct geographic carbon flow. CBA investigates a city's role as a final consumer, and urban consumption-based carbon flow represents both direct and indirect upstream carbon flow caused by its final consumption. The calculation equations in the EE-MSIO model can be referred to (Hu et al., 2016; Liang et al., 2017; Lin et al., 2017). The fundamental input-output balance can be presented as

$$\begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1m} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2m} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & A^{m3} & \cdots & A^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \sum_s y^{3s} \\ \vdots \\ \sum_s y^{ms} \end{pmatrix} \tag{2}$$

and can be easily expressed in matrix format, to address the relationship between final consumption and total output:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{3}$$

where x is the total output, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{A} = \boldsymbol{T}\hat{\boldsymbol{X}}^{-1}$ is the direct requirement matrix. $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief Inverse, which describes all direct and indirect monetary relationships among different sectors.

To calculate the embodied carbon flows ($\boldsymbol{F}$), we extended this economic input-output equation by incorporating the carbon satellite account ($\boldsymbol{E}$) identified as the carbon emissions of each sector. We defined the sectoral direct carbon emission intensity as the amount of impact caused by one unit of total output, shown as $\boldsymbol{e} = \boldsymbol{E}\hat{\boldsymbol{X}}^{-1}$, and the embodied carbon flows $\boldsymbol{F}$ can be calculated with $\boldsymbol{F} = \hat{e}L\hat{y}$. With the $\boldsymbol{F}$ matrix, we obtained the life-cycle carbon flows driven by economic activities like urban (local) final consumption or exports. The carbon flow balance trade ($\boldsymbol{EBT}$) of urban sectors were calculated from the difference of production-based carbon flows ($\boldsymbol{E}$) and consumption-based carbon flows ($\boldsymbol{F}$), *i.e.*, $\boldsymbol{EBT} = \boldsymbol{F} - \boldsymbol{E}$. A positive $\boldsymbol{EBT}$ value indicates a net carbon importer (Consumer), and a negative value indicates a net carbon exporter (Producer).

2.2. Data use

In this study, the environmental satellite account includes direct carbon emissions from Beijing-domestic regions-nations around the world, namely 70 regions with 20 industries each. The carbon emission data for the 40 WIOD global regions are from WIOD database.

For 30 regions (including Beijing) in China, carbon emissions are not officially published annually for each economic sector. Thus, detailed data processing and sources for carbon emissions needed to be defined. The carbon emission inventories considered energy use and non-energy use (only including agriculture production), in the form of carbon dioxide equivalents (CO_2e), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), based on the Kyoto protocol. It reports them together as carbon dioxide equivalents (CO_2e) by global-warming potentials (GWPs) over a 100-year period at the ratio of 1:21:310 for CO_2:CH_4:N_2O. Carbon emissions of 30 Chinese provinces (including Beijing) were calculated based on the IPCC approach. The detailed accounting method description refers to Lin et al. (2013) and Meng et al. (2017a). Activity data were mainly from the China's Provincial Energy Statistics, while some additional agricultural data were from the China Agriculture Yearbook. Emission factors were taken from IPCC guidelines and the National Greenhouse Gas Inventory, referring to Meng et al. (2017a).

3. Results

3.1. Flow analysis

3.1.1. General analysis

In this paper, an EE-MSIO model was employed to trace the carbon flows of Beijing City in 2010 based on PBA and CBA approaches. The PBA approach can account for the carbon flows embodied in products produced locally and distinguish its destinations for local consumption, domestic exports, and foreign exports. The CBA approach can account for carbon flows embodied in products consumed locally and distinguish its origins for local production, domestic imports, and foreign imports. The detailed flow structure can be seen in Fig. 1(a)-(c). In particular:

(1) From Fig. 1(b), production-based carbon flows occurring within urban territorial boundaries were 98.93 Mt CO_2e, of which, 51% flowed inside the city by local consumption, 29% flowed into domestic regions by domestic exports, and 20% flowed into worldwide regions by foreign exports. Consumption-based carbon flows were 210.31 Mt CO_2e, which is 2.13-fold greater than production-based carbon flows. Of these, 24% flowed inside the city due to local production, and 76% flowed outside the city boundary, as indicated by Feng et al. (2014). These data confirmed that the consumer role of the city is largely dependent on products and services produced elsewhere, thus imposing carbon flows to other regions at home and abroad.

(2) From Fig. 1(c), carbon flows embodied in the domestic exported and imported goods and services are traced and quantified in the domestic regions in China. From the flow structure, we can see that the three largest regions for domestic carbon outflow are the Central Coast (23%), North (19%), and Central (15%) regions. This indicates that the carbon flows transferred from these domestic regions were undertaken by Beijing, accounting for 57% of the domestic exported carbon flows occurring within Beijing's geographic boundary. The three largest regions for domestic carbon inflow account for as much as 70% of the carbon flows from domestic imports, respectively, for the North (25%), Northwest (24%), and Central (21%) regions. This is because energy and heavy chemical industries are widely distributed in these regions and exported to provide powerful backup for Beijing's economic development.

(3) From Fig. 1(a), carbon flows, embodied in the foreign exported and imported goods and services, are traced and quantified in the regions worldwide. From the flow structure, we can see that the top three regions for foreign carbon outflows are North America (28%), European Countries (24%), and Other Countries (22%). Consequently, nearly 74% of foreign exported carbon flows occurring within Beijing's geographic boundary were transferred from those three consumers worldwide to Beijing. Beijing outsourced 40%, 12%, and 11% to Other Countries (respectively, East Asia and North America). Thus, the top three foreign regions for carbon inflow account for as much as 63% of the carbon flows from foreign imports.

3.1.2. Interregional carbon flow analysis in China

To accurately trace the carbon flows across the 29 domestic regions

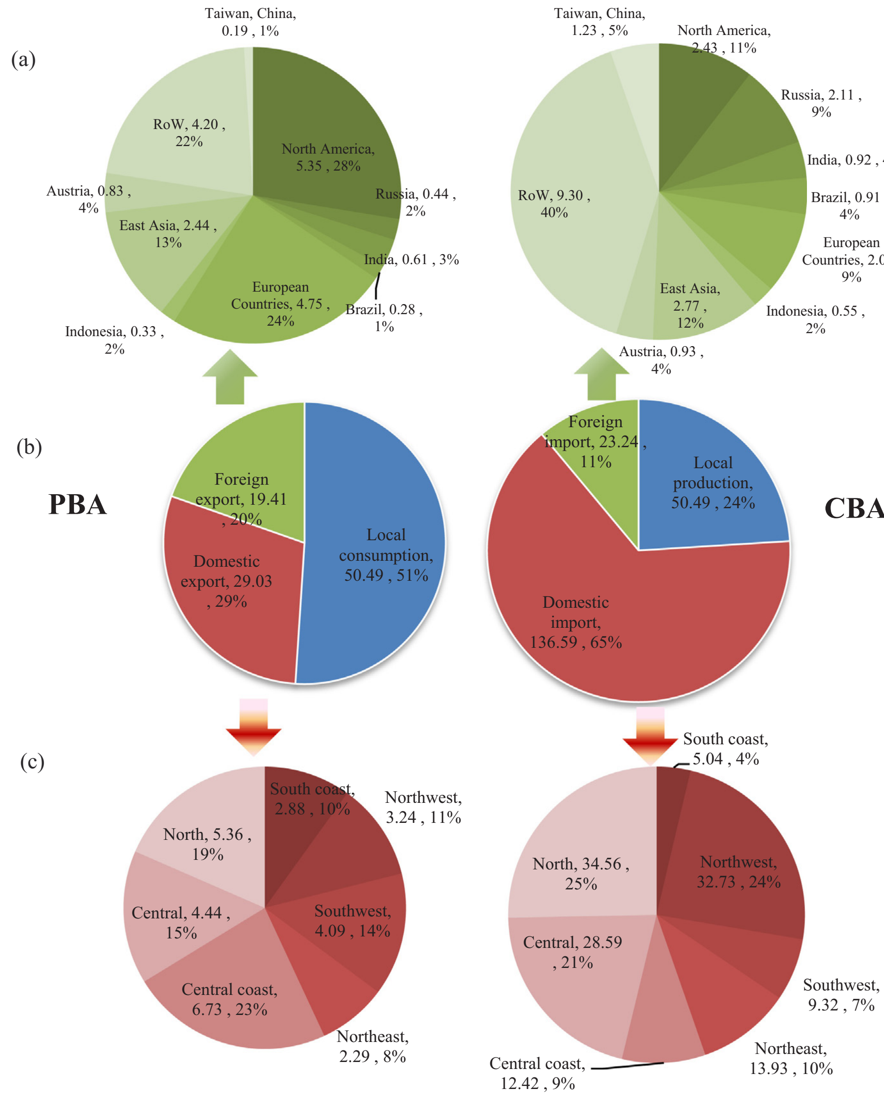


Fig. 1. Structure of carbon flows for Beijing City in 2010 based on PBA and CBA.

(excluding Tibet and Taiwan) in China, precise sources and destinations of the carbon flow embodied in domestic imports and exports of Beijing are presented in Fig. 2.

From Fig. 2(a), 52.24% of domestic imported embodied carbon flows are focused on Hebei, Inner Mongolia, Shanxi, Shandong, and Jiangsu provinces. There are two main reasons for this: One is that it depends on the strongest geographical advantage because these provinces are all close to Beijing City. The other is that it depends on the economic structure of these provinces. In particular, Inner Mongolia and Shanxi are the “Energy Powerful Provinces”, while Hebei, Shandong, and Jiangsu are major economic provinces, possessing a robust and competitive industrial base. For example, Hebei Province produces the most iron and steel, Shandong is one of the strongest agricultural and manufacturing provinces in China, and Jiangsu is a powerful province in the manufacturing industry. Beijing, as a consumer, transfers the embodied carbon emissions caused by the final demand to these provinces by importing raw materials and products.

From Fig. 2(b), 38.41% of domestic exported carbon emissions concentrate on Jiangsu, Tianjin, Shanghai, Hebei, and Henan provinces. Except for the neighboring Hebei and Henan provinces, the other three provinces are economically developed regions, importing high value-added products and services from Beijing to meet their final demand, along with transferring the embodied carbon emissions to Beijing.

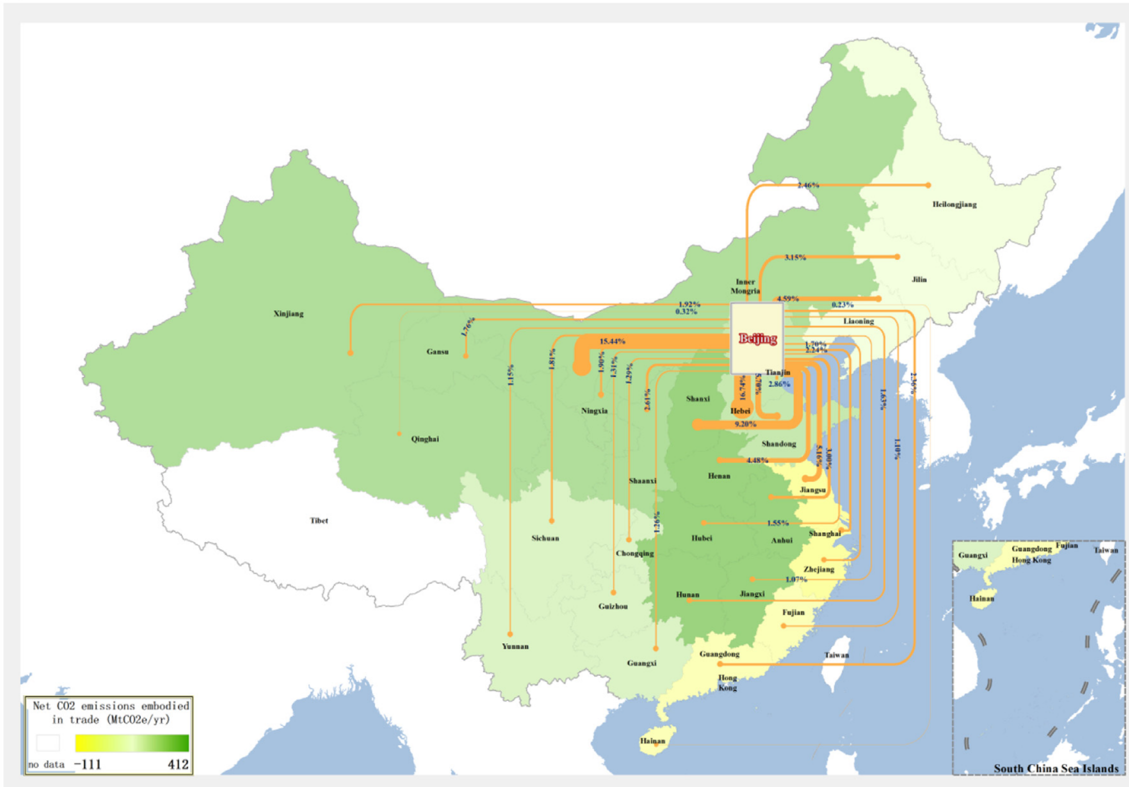
3.1.3. International carbon flow analysis around the globe

To accurately trace the carbon flows across the 39 regions (excluding Rest of the World (RoW) regions, see Table S2) worldwide, the precise sources and destinations of the carbon flow embodied in international imports and exports of Beijing are presented in Fig. 3.

Specifically, 57.65% of the international embodied carbon inflow (excluding the RoW region) was concentrated from Russia (15.10%), the United States (13.84%), South Korea (11.29%), Taiwan (8.86%), and Japan (8.56%). One likely reason for such a distribution lies in the geographical advantage these countries have. In fact, Russia, South Korea, Taiwan, and Japan are located in regions bordering Mainland China. Moreover, another fundamental reason could be their economic structure. As a major energy provider, Russia is the key provider of oil and natural gas to China. Japan and South Korea are large manufacturing countries. Further, as the largest economy in the world, the United States exports primary energy products, finished goods, and services to Beijing. Thus, Beijing, as a consumer, transfers the embodied carbon emissions caused by the final demand to these countries and regions worldwide by importing raw materials and products. In comparison, 57.59% of international carbon outflow (excluding the RoW region) was focused in the United States (29.52%), Japan (10.73%), Germany (6.62%), Australia (5.43%), and South Korea (5.29%).

Above all, the common trade economies among the top three inflow and outflow countries and regions were the United States, Japan, and

(a)



(b)

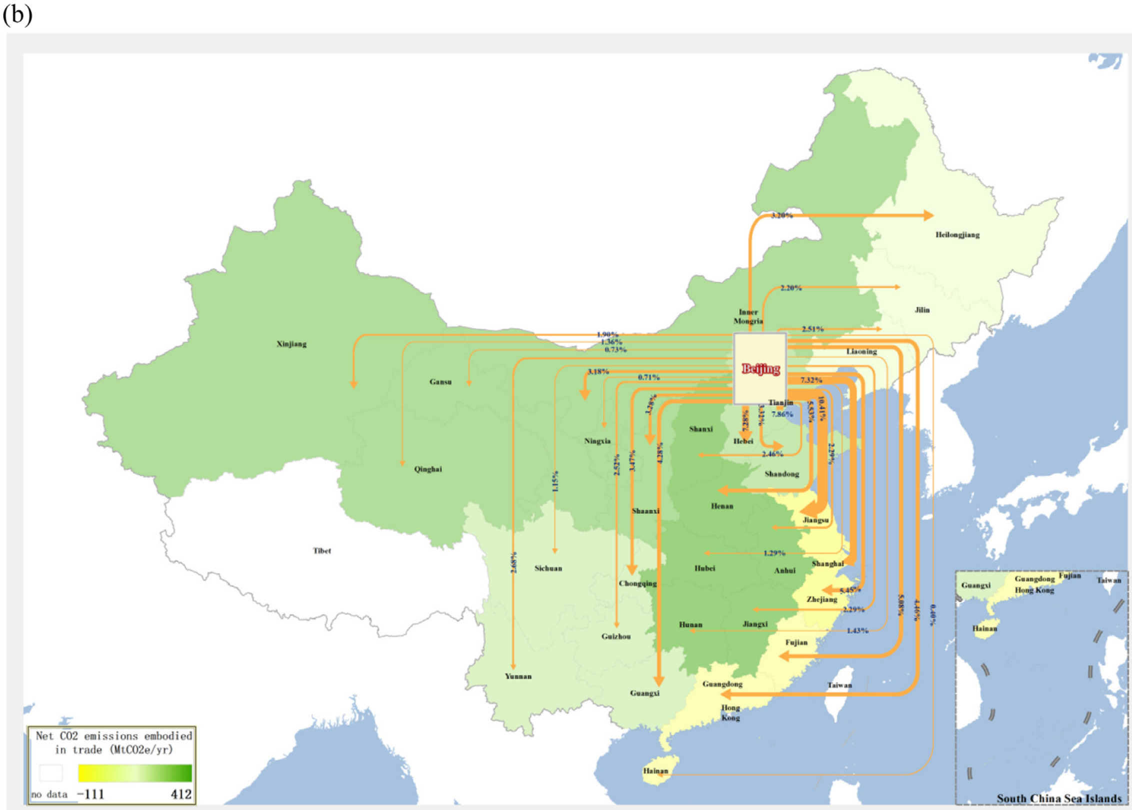


Fig. 2. Accurate origin and destination of carbon flows across China induced by the exports and imports of Beijing in 2010. Note: the widths of the flux correspond to the amount of flows. Circular dots represent the source of flow to Beijing; arrows represent the destination of flow from Beijing. The color for different regions in the map of China represents the extent of net carbon flow by export. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

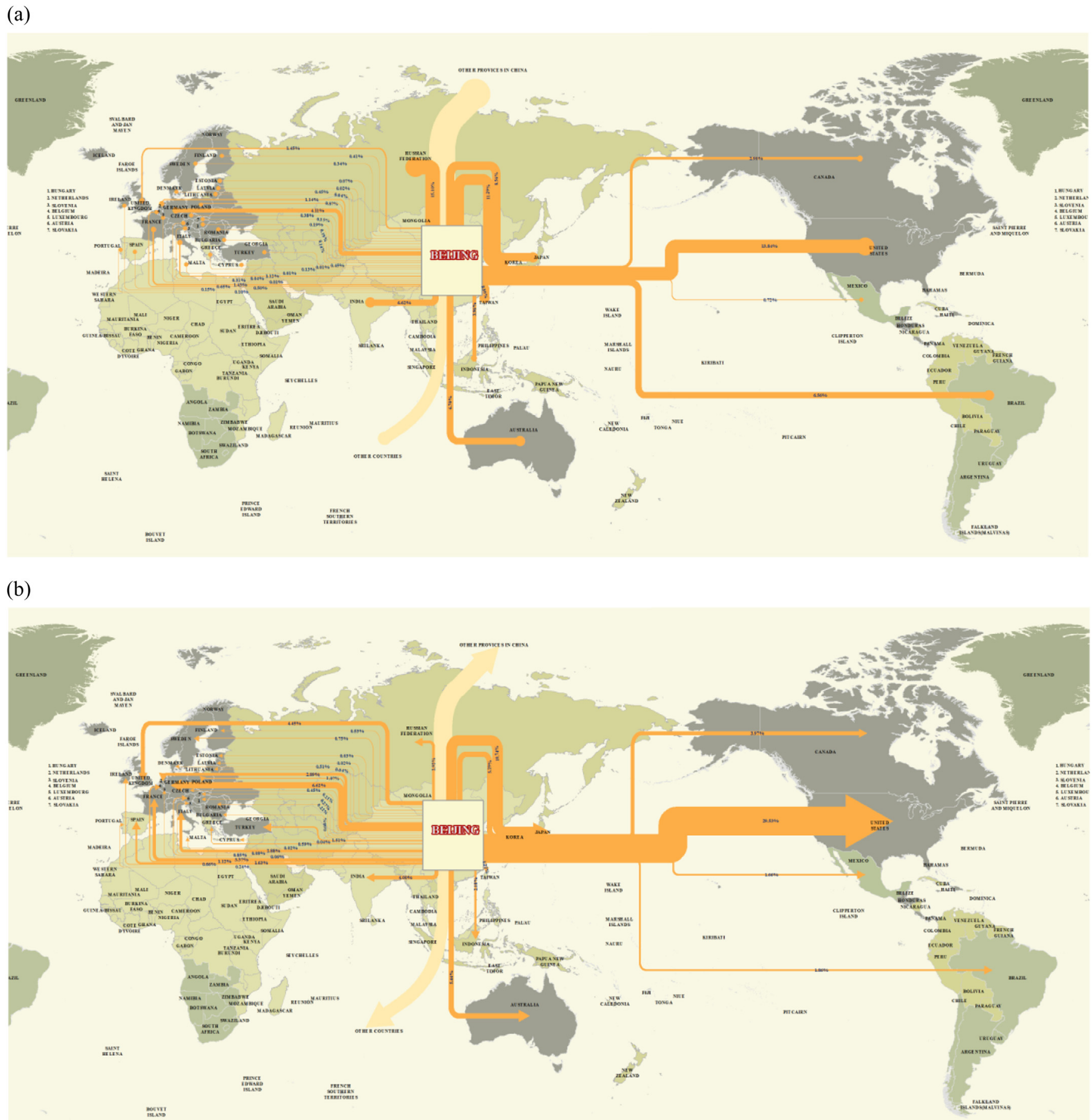


Fig. 3. Accurate origin and destination of carbon flows around the world induced by the exports and imports of Beijing in 2010. Note: The number represents the ratio of Beijing's embodied carbon flow by foreign exports and imports with the targeted region to it with all regions in the worldwide (excluding RoW region). The inflows and outflows of domestic regions and RoW region only represent the direction.

South Korea, indicating that a close exchange of embodied carbon flows exists between Beijing and these three countries. In addition, the carbon embodied in products exported from Beijing also flowed into Germany and Australia, suggesting that these two countries rely on products and services imported from Beijing to meet the energy demands in their domestic markets.

3.1.4. Main features of the carbon flow patterns for Beijing

Generally, open international metropolises are not limited inside a geographical city boundary but flow across multiple regions in the global value chain. In 2010, Beijing's consumption-based carbon flows were 2.13 times that of the traditional production-based carbon flows. In particular, 76% of carbon flows driven by final demand in Beijing were outsourced to domestic and international regions outside of the city boundary. More than half of the inflows were from domestic imports, while only 24% of carbon flows were produced locally. However, approximately 50% of production-based carbon flows were used locally, with the other half used by domestic exports (30%) and international exports (20%). Therefore, it is urgent for policy-makers to govern the carbon emission reduction problems from a multi-region

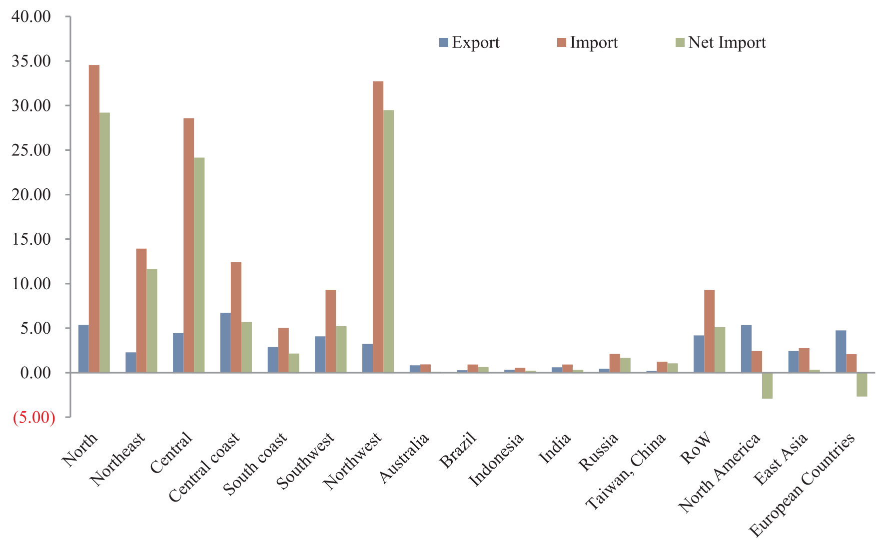


Fig. 4. Carbon balance between Beijing and its trading regions (Mt CO2e).

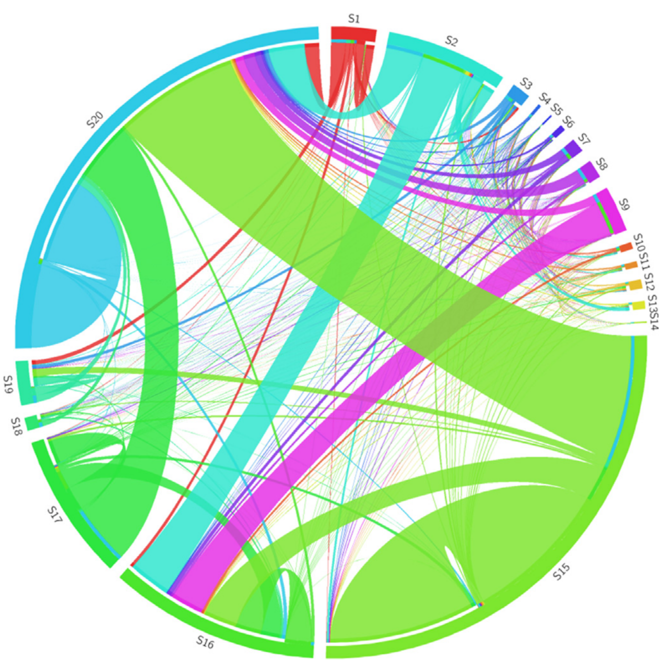


Fig. 5. Industrial structure and intersectoral linkage for local carbon flow in Beijing in 2010. Note: Number S1–20 represents the industrial sector, see Table S1. Taking the carbon flows of sector S15 as an example, the outermost circle represents the sum of both production-based and consumption-based carbon flows. The innermost white arc represents the consumption-based carbon flows, and another colorful arc represents the production-based carbon flows. The lines between S15 and other sectors represent the origins and destinations of carbon flows embodied in local production by sector S15, respectively (width represent the size of flow). The green closed circle line represents the direct carbon flows induced by sector 15 itself. Accordingly, it can reveal the complex inner industrial structure and intersectoral linkage locally. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

coordinated management perspective.

Second, Beijing is typically a net importer of carbon flow (net consumer), which is consistent with Beijing's profile as a consumer metropolis. All seven domestic regions in China were net producers with respect to Beijing, supporting nearly 96.56% of the net carbon inflows driven by Beijing's final demand (see Fig. 4). In 2010, Beijing's net carbon inflows were 111.39 $MtCO_2e$. From Fig. 4, the top three net domestic producers of carbon flows were Northwest China, North China, and Central China, contributing to 26.48%, 26.21%, and 21.68% of the total net carbon inflows. Specifically, the top three net carbon producers at the provincial level were Hebei (North China) (18.63%), Inner Mongolia (Northwest China) (18.11%), and Shanxi (Central China) (10.64%). Note that Beijing appeared to be a net producer of carbon flows for North America and European Countries. Beijing has net exports to these regions of 2.92 and 2.67 $MtCO_2e$, respectively. In particular, the USA, the UK, and Japan are the three largest areas for net exports, to which Beijing had net exports of 2.56, 0.48, and 0.44 $MtCO_2e$, respectively. Therefore, as a net carbon consumption city, Beijing mainly imports carbon flows from domestic regions and developing areas around the world but exports little to developed countries.

Third, Beijing is located at the bottom of the global production supply chain, transferring the embodied carbon flow to the origin by domestic and international imports. Such a trade structure is beneficial to Beijing in terms of carbon emissions reduction (see Fig. S1). Beijing's per capita GDP is ranked second in China. The carbon flow embodied in domestic imported products was 1.56 $tCO_2e/10^4$ Yuan, *i.e.*, four times the intensity of carbon embodied in domestic exports. In parallel, carbon flow embodied in international imports was 0.80 $tCO_2e/10^4$ Yuan, *i.e.*, 1.5 times the intensity of the carbon flow embodied in international exports. However, for China, the intensity of carbon embodied in international exports was 1.48 $tCO_2e/10^4$ Yuan, *i.e.*, 2 times the intensity of carbon embodied in international imports. These results suggest that China's trade volume is characterized by carbon-intensive exports. Beijing mainly exports low carbon products with high values to developed countries and imports carbon-intensive products from domestic regions in China.

3.2. *Industrial structure analysis*

3.2.1. *Local intersectoral structure analysis for carbon flows*

In this study, the key inner industrial structure, linkage, and drivers of carbon flows in the city were effectively identified both from local inner intersectoral flow analysis and external regional spatial distribution analysis. From a local perspective, the complex inner industrial structure and intersectoral linkage were analyzed both from production and consumption perspectives (See Fig. 5). From Fig. 5, 66.08% of production-based carbon flows are focused on the Electricity (S15), Transport (S17), and Mining (S2) sectors, respectively, accounting for 39.71%, 13.84%, and 12.53%. Of this, for the destination of direct carbon flows in the downstream supply chain, nearly 45.45% of direct

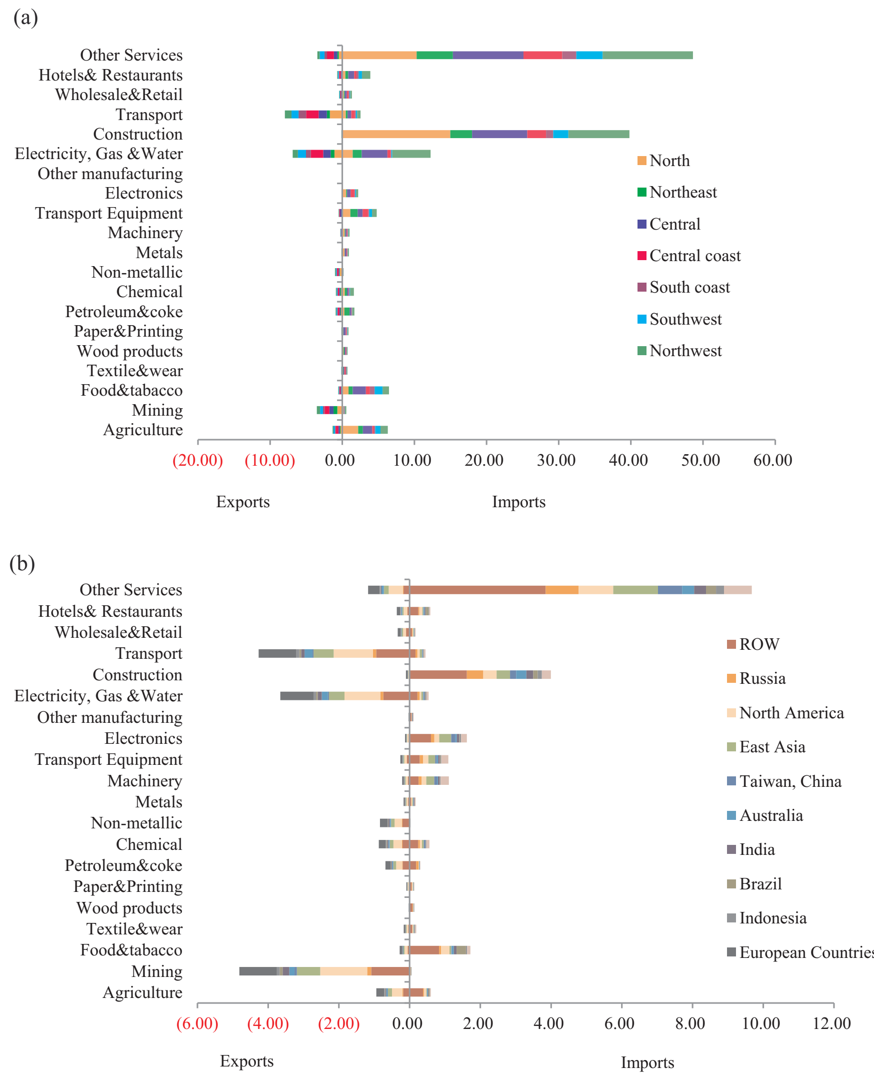


Fig. 6. Spatial distribution for industrial carbon flows in domestic regions and worldwide in Beijing in 2010. (Mt CO_2e).

carbon flows of Electricity (S15) was induced by sector-self, 52.83% of direct carbon flows of Transport (S17) went to Other services (S20), and 41.26% of direct carbon flows of Mining (S2) went to Construction (S16).

Meanwhile, nearly 80.38% of consumption-based carbon flows are focused on Other services (S20), Construction (S16), and Electricity (S15), respectively, accounting for 42.67%, 19.82%, and 17.90%. Of this, for the origin of carbon flow in the upstream supply chain, nearly 33.67% of embodied carbon flows of Other services (S20) was from Electricity (S15), 24.35% of embodied carbon flows of Construction (S16) was from Mining (S2), and 94.14% of embodied carbon flows of Electricity (S15) was from sector-self. In total, carbon flows of the key industrial sectors can help to explain the characteristic of urban flow in the whole perspective.

3.2.2. Regional spatial distribution for key industrial carbon flows

Based on the external regional perspective, the spatial distribution structure for industrial carbon flows in domestic regions and worldwide are analyzed in Fig. 6.

The detailed key industrial structure of production-based carbon flows can be seen in Table 1. Taking the production-based carbon flow of the Electricity sector (S15) as an example, Sectoral Production-based Carbon (SPC) took up 30.91% of the Urban Production-based Carbon (UPC). Of this, 65.57% of SPC was used for Local Consumption (LCC), and 34.43% of SPC was embodied in Exports (22.47% embodied in Domestic Exports (DEC) and 11.97% embodied in International Exports (IEC)). For carbon embodied in exports, 65.24% of carbon outflowed into domestic regions, of which 37.61% focused in the North, Central coast, and Southwest, while 34.76% of carbon outflowed into international regions, of which 25.74% was focused in North America, European Countries, and the RoW.

The detailed key industrial structure of consumption-based carbon flows can be seen in Table 2. Taking the consumption-based carbon of Electricity sector (S15) as an example, Sectoral Consumption-based Carbon (SCC) accounted for 10.68% of the Urban Consumption-based Carbon (UCC), of which, 43.08% of SCC was used for Local Production (LPC), and 56.92% of SCC was from imports (54.52% embodied in Domestic Imports (DIC) and 2.40% for International Imports (IIC)). For carbon embodied in imports, 95.78% of carbon inflow was from domestic regions, of which 80.69% was focused in the North, Central, and Northwest regions, while only 4.22% of carbon was inflowing from international regions (of which 2.74% was from the RoW, Russia, and European Countries). Other industrial structures and spatial distributions of carbon flow from both the production and consumption perspective can be seen in Fig. 6.

Based on the specific production-based industrial flow features, we can conclude that the Electricity (S15) and Transport (S17) sectors are the main direct carbon emitters, accounting for nearly half of the total

Table 1
Industrial structure of production-based carbon flow of Beijing in 2010 ($MtCO_2e$).

Sector	Total		Local Consumption				Domestic Exports			International Exports				
	SPC	SPC/UPC (%)	LCC	LCC/SPC (%)	DEC	DEC/SPC (%)	DEC/(DEC + IEC) (%)	Main domestic export regions		IEC	IEC/SPC (%)	IEC/(DEC + IEC) (%)	Main international export regions	
								Top three	Ratio for (DEC + IEC) (%)				Top three	Ratio for (DEC + IEC) (%)
Electricity	30.58	30.91	20.05	65.57	6.87	22.47	65.24	North, Central coast, Southwest	37.61	3.66	11.97	34.76	Northern America, European Countries,	25.74
Transport	19.21	19.42	6.99	36.39	7.96	41.44	65.09	North, Central,	37.37	4.27	22.23	34.91	RoW	25.51
Mining	14.67	14.83	6.33	43.15	3.53	24.06	42.33	Central coast	23.02	4.81	32.79	57.67		41.73
Sub-total	64.46	65.16	33.37	51.77	18.36	28.48	59.04		33.25	12.74	19.76	40.96		29.94
Totally for all sectors (UPC)	98.93	100.00	50.49	51.04	29.03	29.34	59.93		34.12	19.41	19.62	40.07		29.50

Note: SPC refers to Sectoral Production-based Carbon; UPC refers to Urban Production-based Carbon; LCC refers to Carbon embodied in Local Consumption; DEC refers to Carbon embodied in Domestic Exports; IEC refers to Carbon embodied in International Exports; SPC = LCC + DEC + IEC; UPC = $\Sigma S_i PC$, i is for the sector.

Table 2
Industrial structure of consumption-based carbon flows of Beijing in 2010 ($MtCO_2e$).

Sector	Total		Local Production		Domestic Import					International Import				
	SCC	SCC/UCC (%)	LPC	LPC/SCC (%)	DIC	DIC/SCC (%)	DIC/(DIC + IIC) (%)	Main domestic import regions		IIC	IIC/SCC (%)	IIC/(DIC + IIC) (%)	Main international import regions	
								Top three	Ratio for (DIC + IIC) (%)				Top three	Ratio for (DIC + IIC) (%)
Other services	81.35	38.68	23.08	28.37	48.6	59.74	83.39	North, Central, Northwest	55.92	9.68	11.90	16.61	RoW, Russia, North Amercia	9.88
Construction	54.51	25.92	10.72	19.67	39.8	73.01	90.89		71.02	3.99	7.32	9.11	RoW, Russia, East Asia	5.62
Electricity	22.47	10.68	9.68	43.08	12.25	54.52	95.78		80.69	0.54	2.40	4.22	RoW, Russia, European Countries	2.74
Sub-total	158.33	75.28	43.48	27.46	100.65	63.57	87.63		64.43	14.21	8.97	12.37	RoW, North Amercia,	7.65
Totally for all sectors (UCC)	210.31	100.00	50.49	24.01	136.59	64.95	85.46		59.98	23.24	11.05	14.54	East Asia	9.07

Note: SCC refers to Sectoral Consumption-based Carbon; UCC refers to Urban Consumption-based Carbon; LPC refers to Carbon embodied in Local Production; DIC refers to Carbon embodied in Domestic Imports; IIC refers to Carbon embodied in International Imports; SCC = LPC + DIC + IIC; UCC = $\Sigma S_i CC$, i is for the sector.

direct carbon flow in Beijing in 2010. Local electricity demands drove 65.57% of direct carbon flow, while 63.67% of direct carbon flow in the transport sector (S17) was driven by domestic (41.44%) and international (22.23%) exports. In total, these key industrial sector flows can help to explain the characteristics of Beijing's carbon flow. In particular, half of the flow is used locally, 30% is used for domestic exports, and 20% is used for international exports. The main exporting regions are, similarly, focused in North, Central, and Central coast domestic regions, in addition to North American, European Countries, and the RoW in international regions.

Based on the specific consumption-based industrial flow features, we can conclude that Other services (S20), Construction (S16), and Electricity (S15) sectors were the main embodied carbon contributors, accounting for 77.28% of total embodied carbon flow in Beijing in 2010. In particular, 27.46% of the embodied carbon of these three sectors was driven locally, and 59.74%, 73.01%, and 54.52% of the sectoral carbon of Other services (S20), Construction (S16), and Electricity (S15) were driven by domestic imports respectively. The North, Central, and Northwest regions were the top domestic imported regions for embodied carbon for the industrial sectors. The RoW, North America, East Asia, and European countries are the main international embodied carbon imported sources. In total, these specific features of the consumption-based industrial structure for carbon flow can help explain why Beijing presents its complex and differential flow characteristics. In conclusion, the developed domestic and international trade structure is the main driver for the interconnectedness of embodied carbon flow. Nearly 76% of embodied carbon occurred outside the city boundary via trade.

3.2.3. Industrial balance analysis

Fig. 7 shows that except for the Mining (S2), Non-metallic (S9), and Transport (S17) sectors, all of the other industrial sectors generated a net inflow of carbon for Beijing in 2010. Thus, Beijing was a net carbon importer from a global perspective.

The results show that 80.46% of total net inflows of embodied carbon (129.98 $MtCO_2e$) were focused on the Other services (S20, 53.65 $MtCO_2e$), Construction (S16, 43.57 $MtCO_2e$), and Food & Tabacco (S3, 7.36 $MtCO_2e$) industries. For the net inflow of embodied carbon in Other services (S20) sector, 84.15% was from domestic net inflow, and 15.85% was from international net inflow. For the net inflow of embodied carbon in the Construction sector (S16), 91.07% was from domestic net inflow and 8.93% from international net inflow. For the net inflow of embodied carbon in the Food & Tobacco sector (S3), 80.42% was from domestic net inflow and 19.58% from international net inflow. Consequently, key materials, including food, energy, service, cement, and others, are imported from outside the city to meet final demands and, then, drive the related carbon emissions transferred to the upstream production regions. These data indicate that more than 80% of net carbon flows of those industrial sectors were transferred to the domestic regions in China by domestic imports.

From Fig. 7, Transport (S17), Mining (S2), and Non-metallic (S9) are net outflows of embodied carbon in Beijing, accounting for 49.68%, 41.51%, and 8.82% of the total net outflow of embodied carbon (18.6 $MtCO_2e$), respectively. For the net outflow of embodied carbon in the Transport sector (S17), 58.66% was for domestic net outflow and 41.34% for international net outflow. For the net outflow of embodied carbon in the Mining sector (S2), 38.36% was for domestic net outflow and 61.64% for international net outflow. For the net outflow of embodied carbon in the Non-metallic sector (S9), 50.46% was for domestic net outflow and 49.54% for international net outflow. This was due to the large export volumes in the transportation and mining industries, with each accounting for 10.72% and 12.54% of the total export volume of Beijing, respectively. Moreover, the large export volume is attributed to the fact that state-owned energy enterprises and Minstry of Transport are headquartered in Beijing, and their output is calculated as the energy production and transport output of Beijing.

4. Conclusions and discussions

In this study, an EE-MSIO model was applied to accurately trace the spatial distribution, both for the origin and for destination, of Beijing's carbon flows in the local, domestic regions, and worldwide economies for the year 2010. The carbon flows structure, based on PBA and CBA approaches, was analyzed through the EE-MSIO model. In terms of carbon flows of Beijing City, this research indicated that the consumption-based carbon (210.31 $MtCO_2e$) is 2.13 times the production-based carbon (98.93 $MtCO_2e$), while 76% of consumption-based carbon emissions occurred outside Beijing's geographic boundary. From a production perspective, 50% of the production-based carbon emissions were from local production activities for local consumption, 30% for domestic export, and 20% for international export. Through accurate carbon flows mapping, it emerged that neighboring Hebei Province is the largest origin of imported carbon, while Jiangsu is the largest destination of exported carbon for Beijing. For embodied carbon flows derived from international trade, Russia and the U.S. are the main embodied carbon importing countries. In parallel, the U.S. and Japan are the main embodied carbon exporting countries.

Current urban carbon reduction targets are set on the basis of the production-based carbon inventory. Production-based carbon flows, which occur within urban territorial boundaries, are traced, but

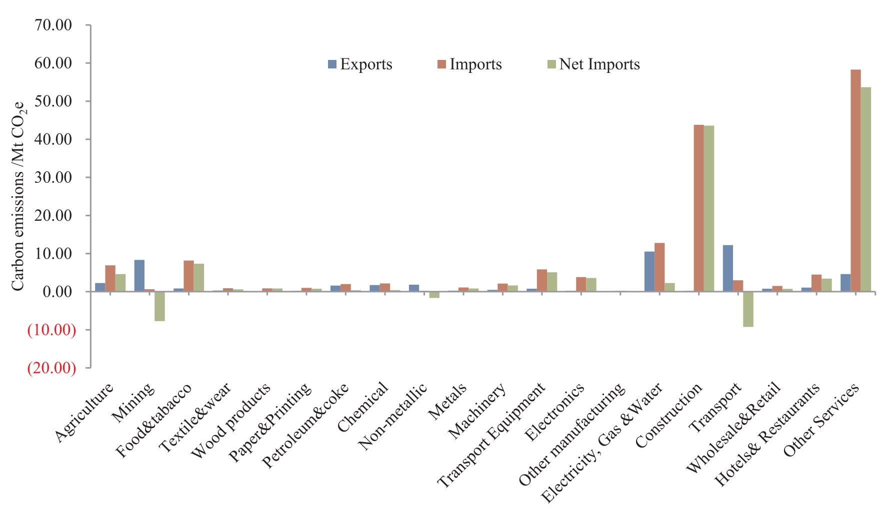


Fig. 7. Balance feature of carbon flows for industrial sectors for Beijing in 2010.

indistinguishable for the carbon flows' destinations, including local consumption, domestic exports in China and foreign exports worldwide (Shan et al., 2016). Those values are necessary but insufficient both for assessing the contribution of human activities to carbon emissions and for guiding the measures of carbon emission mitigation. Because of a small fraction of carbon emissions induced by local production, urban policymakers will miss many opportunities to benefit the global environment if their efforts are directed only toward reduction of reported local emissions inside city boundaries. Compared to PBA, CBA represents substantial direct and indirect carbon emissions from local production and domestic and international imports, representing the emissions induced by the final purchases of finished products. The use of CBA can avoid the carbon emission leakage associated with trade, thereby linking economic activity with emissions and increasing mitigation options (Peters and Hertwich, 2008b). In addition, it can also help urban government to widen and extend its policy options concerning local consumption patterns and regional collaboration on carbon emissions mitigation. Meanwhile, PBA may mislead urban administrative managers to eliminate the energy intensive industries to fulfill urban carbon reduction targets. However, carbon emissions embodied in trade flow following the exchange of products and services. The carbon reduction target at the larger country scale may not be achieved, even considering a short-term increase, because of the demand of new construction of manufacture facilities (Guan et al., 2014).

Currently, Beijing's non-capital function will be orderly undertaken to the Xiongan New Area, which is one of the central issues for Beijing-Tianjin-Hebei coordinated development in China (Wu and Liu, 2017). The growth of the tertiary industry ratio of Beijing will strengthen its characteristic as a consumer-dominated international metropolitan city. Meanwhile, Beijing, as one of the key node cities in the global Belt and Road Initiative, is experiencing global 'carbon transfer' accompanied by frequent goods and services trade throughout the whole supply chain. As a global shared responsibility, urban carbon emissions reduction requires the local government look beyond its own territorial jurisdiction, and regional collaboration is the main future trend. Results in this study indicated that the realization of carbon reduction responsibilities of cities can be accelerated from a consumption perspective. Strengthening regional coordination and adjusting the regional trade structure should be the main measures to tackle global climate change in the future. The pilot carbon trading systems conducted in seven cities in China has improved the regional cooperation mechanisms on mitigation domestically. Additionally, the Clean Development Mechanism (CDM) within China may encourage further cooperation between cities and their neighbors. In particular, cities may invest in their surrounding areas and obtain carbon emissions permits under such a mechanism (Mi et al., 2016). Urban consumption patterns should also be concentrated on to guide the setting of urban carbon mitigation targets, being more instructive and effective, especially for megacities as net consumers like Beijing.

In this study, some limitations still exist with respect to both methodology and data. First, for the EE-MSIO model was employed for the year 2010, and the age of the data is a significant shortcoming. However, the 2010 China MRIOT is the most current available dataset. Several methodologies, incorporating multiple spatial scales (*i.e.*, global, supra-national, national, and regional), were developed to capture the heterogeneity of regions within the global economy (Bachmann et al., 2014; Wenz et al., 2014; Wang et al., 2015). However, the existing disadvantage is increased data inaccuracy, due to the disaggregation approximations of trade flows from one region in one country to another region in another country. In the EE-MSIO model, the main limitation comes from the estimation of trade relationships among Chinese subnational regions and world regions. We lack current trade data to benchmark our estimation. However, results from previous studies with the same estimation indicate confidence in this method. For example, the summary of the exported greenhouse gas for each Chinese province, which is calculated from the estimated MRIO model (Liu et al., 2016), accurately equals the results from the model, where China is taken as a single region (Davis and Caldeira, 2010) instead of several subnational regions. Second, the limitations of IOA are well documented in the literature (Wiedmann, 2009), such as the data uncertainty due to sectoral aggregation error. In this study, the sectors were aggregated into 20 for concordance, which, might reduce the accuracy of the results. Third, for the environmental inventory data, carbon flow data in each Chinese region cannot be completely derived from statistics. Consequently, they are often estimated by down-scaling available datasets at higher administrative levels. Fourth, Beijing was chosen as the case study as a municipality level of city. The advantage is that data on economic trade and environmental activities can be gained from the city's statistical yearbook and other governmental reports. However, in the EE-MSIO model, this is only applicable for Beijing, Shanghai, Tianjin, and Chongqing (the four municipalities in China) as separate regions in the China MRIOT linked to the global economic system. Thus, presently, the model lacks general applicability for most cities.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.06.044.

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